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METHODOLOGY INVESTIGATION

FINAL REPORT

DESERT ATMOSPHERIC EFFECTS ON TARGET ACQUISITION

By

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U.S. ARMY DUGWAY PROVING GROUND
DUGWAY, UTAH 84022-5000

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SUBJECT: Methodology Investigation Final Report, Desert Atmospheric Effects on Target Acquisition, TECOM Project No. 7-CO-M92-DPD-009

1. Subject report is approved.

2. Point of contact at this headquarters is Mrs. Cyndie McMullen, AMSTE-TC, amstetcd@apg-9.apg.army.mil, DSN 298-1469.

FOR THE COMMANDER:

Kenneth R. Balliet

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Deleterious effects on electrooptical wave propagation through the atmosphere's surface boundary layer are caused by temperature and humidity fluctuations. These effects on the refractive index are parameterized in the form of the refractive index structure parameter C_n^2, which is a function of the temperature (C_T^2) and humidity (C_Q^2) structure parameters and the temperature-humidity cross-structure parameter (C_{TQ}). The magnitude of C_{TQ} is determined by the frequency-dependent correlation r_{TQ} between temperature and humidity fluctuations. Many researchers assume, based on dimensional analysis techniques, that r_{TQ} is unity and treat C_{TQ} and C_n^2 as Monin-Obukhov similarity variables. This assumption can lead to large errors for propagation modeling, particularly when applied to infrared and millimeter wavelength propagation in desert atmospheric conditions. Measurements needed to define r_{TQ} in a desert environment are lacking due to instrumentation deficiencies. Additional instrumentation and methodology development is needed to define temperature-humidity correlation effects on C_n^2. Target acquisition models can then be updated to provide more reliable predictions of atmospheric effects on target acquisition.

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SECTION 1. SUMMARY

1.1 BACKGROUND

Variations in the atmospheric refractive index produce adverse effects on electrooptical wave propagation such as image blurring, beam wander, and laser scintillation. Refractive index inhomogeneities are primarily due to atmospheric temperature and humidity fluctuations, with a minor contribution from pressure fluctuations. The intensity of adverse atmospheric effects on wave propagation can be quantified using the refractive index structure parameter C_n^2, which is the spatially-normalized covariance of the refractive indices measured simultaneously at small separation distances. C_n^2 is a function of the temperature (C_T^2) and humidity (C_Q^2) structure parameters and the temperature-humidity cross-structure parameter C_{TQ}, the latter being a function of the frequency-dependent correlation (coherence) between temperature and humidity. The correlations between temperature and humidity that have the greatest effect on wave propagation are those occurring within turbulence elements equivalent in size to the first Fresnel zone of the propagating wave. Consequently, quantification of temperature-humidity coherence effects on optical through millimeter-wave (mmw) propagation requires instrumentation capable of high frequency temperature and humidity measurements.

The state of the turbulent surface boundary layer (SBL) is conveniently parameterized for modeling applications using Monin-Obukhov similarity (MOS) theory. MOS is a form of dimensional analysis (a technique originally developed to solve engineering fluid dynamics problems) applied to second order statistics of SBL scalar quantities for the purpose of reducing these statistics to common "universal" forms. For horizontally homogeneous and temporally stationary conditions, MOS scaling provides sets of empirical equations that describe "properly normalized" statistics as functions of the dimensionless stability parameter z/L, where z is height above the surface and L is the Obukhov length. Several authors have used dimensional analysis arguments to suggest that C_n^2 is a MOS quantity. Mathematically, this suggestion is very convenient because it allows simplified structure function modeling for atmospheric propagation effects. Also, it permits the computation of path-averaged stability and heat flux from dual-wavelength scintillation measurements. Unfortunately, the real SBL does not long remain temporally stationary or spatially homogeneous, particularly for a highly variable constituent like water vapor, and the surface introduces boundary effects that invalidate conventional dimensional analysis arguments. The uncertainties in wave propagation modeling arising from the limitations of MOS theory are particularly severe for infrared and millimeter wavelengths over surfaces, such as deserts, that exhibit moisture deficits.

1.2 PROBLEM

At infrared and millimeter wavelengths, scintillation effects over moist or wet surfaces are primarily due to contributions from the humidity structure function, but over dry surfaces temperature-humidity coherence effects become the predominant factor. Although temperature-humidity coherence over moist or wet surfaces has been the subject of research for several decades, there is

little comparable published information for dessicated surfaces, probably because of the difficulty of obtaining adequate high frequency humidity measurements in dry conditions. This knowledge gap has potentially serious implications for electrooptical wave propagation modeling, including target acquisition modeling.

1.3 OBJECTIVES

The objectives of this methodology investigation were to: (1) consolidate the available theory and measurements related to the refractive index structure parameter and temperature-humidity coherence, and (2) initiate a measurement program to define temperature-humidity coherence over a dry surface.

1.4 PROCEDURES

A considerable body of literature on the theory, measurement, and modeling of the refractive index structure parameter was reviewed, and the limitations of present dimensional analysis techniques in the form of MOS scaling for SBL scalars were examined. The implications of deficiencies in MOS prescriptions for scintillation modeling, particularly at millimeter wavelengths in desert terrain, were defined. A prototype fast-response humidity sensor with the potential of making the measurements needed to determine temperature-humidity coherence was tested under desert atmospheric conditions.

1.5 RESULTS

The literature review revealed bounds on the applicability of MOS dimensional analysis techniques for the temperature-humidity cross-structure term and refractive index structure parameter. Fast-response temperature and humidity measurements suggest that there is a breakdown of temperature-humidity coherence (i.e., a decrease in correlation) for turbulence scales of 1 m or less. Available evidence also suggests that temperature-humidity coherence diminishes as a surface dries, but definitive measurements of this effect remain unavailable. A prototype fast-response humidity sensor with minimal flow distortion was tested at Dugway Proving Ground (DPG) and found to have problems with: (1) overheating during exposure to desert temperature extremes, (2) inadequate signal-to-noise ratio (SNR), (3) motor noise and speed control, and (4) sun glint interference. Consequently, the data from this instrument were determined to be unusable.

1.6 CONCLUSIONS

The available measurements indicate that: (1) the temperature-humidity cross-structure term and refractive index structure parameter cannot be treated as MOS quantities, and (2) the temperature-humidity coherence cannot be assumed to be unity (as is commonly done in wave propagation modeling), especially in a desert environment. Temperature-humidity coherence is likely to be influenced by local terrain factors not included in MOS analyses, such as differential heating and radiative transfer from the ground surface and the accompanying local changes in surface evapotranspiration. These effects are

believed to create sufficient inhomogeneity and nonstationarity to seriously violate MOS assumptions. Deficiencies in the MOS scaling algorithms currently used to calculate the refractive index structure parameter in target acquisition models render their results suspect. This problem is especially acute for infrared and mmw propagation in desert terrain where the uncertainties in the current refractive index structure parameter estimates are greatest. Definitive measurements over dry surfaces are lacking due to instrumentation deficiencies.

1.7 RECOMMENDATIONS

Surface effects on temperature-humidity coherence remain a major source of uncertainty, particularly for desert atmospheric conditions. Consequently, wave propagation models should include error bars reflecting this uncertainty. Further efforts are needed to develop an instrument that can make high frequency temperature and humidity measurements of sufficient quality for temperature-humidity coherence computations. The most fruitful approach for this instrument will likely be a vertical-axis sonic anemometer/thermometer integrated into a coincident path with a differential absorption hygrometer. This instrument cluster should be designed for a path length of 15 to 20 cm, producing low-noise, undistorted, and unaliased water vapor measurements at a frequency of 10 Hz or higher with an accuracy of ± 0.05 g m^{-3}. The design, construction, and testing of this instrument could be accomplished through Small Business Innovation Research (SBIR) funding. An instrument of this type would have research, commercial, and military applications. Instrument development should be followed by field tests to define temperature-humidity coherence as a function of surface and atmospheric conditions, culminating in a methodology to incorporate these effects into an expanded MOS theory, when possible, and to define the uncertainties when MOS techniques cannot be properly applied. Target acquisition models should then be updated to provide more reliable predictions of atmospheric effects on target acquisition.

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SECTION 2. DETAILS OF THE INVESTIGATION

2.1 REVIEW OF ATMOSPHERIC REFRACTION AND MOS THEORY

Fluctuations in the atmospheric refractive index n′ are related to fluctuations in temperature T′ and humidity Q′ by

$$n' = \frac{A_T T'}{\langle T\rangle} + \frac{A_Q Q'}{\langle Q\rangle} \tag{1}$$

where $\langle T\rangle$ and $\langle Q\rangle$ are the mean values of temperature and absolute humidity, A_T and A_Q are dimensionless, wavelength-dependent temperature and humidity sensitivity coefficients, and T′and Q′ represent single realizations of temperature and humidity fluctuations. Expressed in structure parameter form, Equation (1) becomes (Hill et al., 1980)

$$C_n^2 = \frac{A_T^2\, C_T^2}{\langle T\rangle^2} + \frac{A_Q^2\, C_Q^2}{\langle Q\rangle^2} + 2\,\frac{A_T\, A_Q\, C_{TQ}}{\langle T\rangle\langle Q\rangle} \tag{2}$$

where C_n^2, C_T^2, and C_Q^2 are respectively the refractive index, temperature, and humidity structure parameters and C_{TQ} is the temperature-humidity cross-structure parameter. Because pressure fluctuation contributions to C_n^2 are generally several orders of magnitude lower that contributions by temperature and humidity fluctuations (Hill et al., 1980), pressure fluctuations are neglected in Equation (2).

The relationship shown in Equation (2) between C_n^2 and the temperature and humidity structure parameters and the cross-structure parameter is broadly applicable to the real part of the refractive index extending from the visible through infrared to radio wavelengths. The contributions of the three terms in Equation (2) to C_n^2 vary with the frequency-dependent sensitivity coefficients and the degree of correlation between temperature and humidity at the varying scales of turbulence that determine the magnitude of the C_{TQ} term.

The principal problem in applying Equation (2) is that C_{TQ} is poorly known. The magnitude of C_{TQ} is directly related to the degree of coherence (frequency-dependent correlation, also known as spectral correlation coefficient) between the temperature and humidity fluctuations. In principle, the temperature-humidity coherence r_{TQ} can be obtained from spectrum analysis, which involves the transformation of fluctuating temperature and humidity time series data into the frequency domain where variance energy is decomposed into independent spectral wavelength bands. Temperature and humidity signals in the frequency domain are composed of in-phase (0° and 180° delay) and out-of-phase (90° advance or delay) components, which are known as the cospectrum Co_{TQ} and quadrature, respectively. C_{TQ} is related to Co_{TQ} and r_{TQ} by (Kohsiek, 1988)

$$C_{TQ} \equiv Co_{TQ}\sqrt{C_T^2\, C_Q^2} = r_{TQ}\sqrt{C_T^2\, C_Q^2} \tag{3}$$

Because it is difficult in practice to obtain measurements of sufficient quantity and quality to calculate r_{TQ} directly, it is convenient to make the assumption that r_{TQ} is unity. The cross-structure contribution to C_n^2 can then be approximated by

$$\frac{C_{TQ}}{\langle T\rangle\langle Q\rangle} = \pm\left[\frac{C_Q^2}{\langle Q\rangle^2}\,\frac{C_T^2}{\langle T\rangle^2}\right]^{1/2} \tag{4}$$

The rationale for the assumption that the temperature-humidity coherence r_{TQ} is unity comes from the dimensional analysis techniques developed for fluid dynamics applications. The basic tenet of dimensional analysis is that, by a proper combination of pertinent variables, dimensionless parameters can be formed that behave in predictable (universal) ways. Dimensional analysis results in a set of empirical relationships that are self-similar (i.e., exhibit similar behavior for all conditions where the dimensionless parameter has the same value). The most familiar fluid dynamical dimensionless parameters are the Reynolds number, a ratio of viscous to inertial forces, and the Mach number, a ratio of velocity to speed of sound.

Dimensional analysis techniques developed for fluid dynamics applications have been widely applied to the surface boundary layer (SBL), the portion of the atmosphere extending from the viscous layer at the earth's surface to several meters to tens of meters above the surface. Most U.S. Army operations, particularly those involving line-of-sight electrooptical propagation, take place within the SBL. SBL dimensional analysis is known as Monin-Obukhov similarity (MOS) theory. MOS theory defines SBL quantities as functions of four variables: (1) heat flux $\langle w'T'\rangle$, (2) buoyancy T/kg, (3) momentum flux $\langle u'w'\rangle$, and (4) height z above the surface, which is formed into the dimensionless ratio z/L where the Obukhov length L is given by

$$L = \frac{-\langle u'w'\rangle^{3/2}\,\langle T\rangle}{\langle w'T'\rangle\, kg} \tag{5}$$

In the above discussion, T is the absolute temperature, w is the vertical wind velocity, u is the alongwind component of the wind, k is the von Karman constant (0.4), and g is the gravitational acceleration. The fluctuating quantities u', w', and T' represent differences between an individual measurement and its time-averaged mean value ($u' = u - \langle u\rangle$, for example).

There are several significant difficulties in applying dimensional analysis techniques to the SBL. First, similarity techniques are strictly applicable only for spatially homogeneous and temporally stationary conditions

(i.e., conditions that are invariant in space and time). These conditions are seldom observed in the real SBL. Second, the boundaries, especially the earth's surface, act as a significant source or sink for many of the quantities (temperature, moisture, aerosols, etc.) for which MOS scaling is desirable. Third, some of the quantities subjected to MOS scaling defy standard dimensional scaling because they are second order statistics that arise from nonlinear combinations of scalar variables.

The implications of MOS theory for SBL scalar quantities are addressed by Hill (1989), who shows that any second order statistic of a fluctuating scalar quantity divided by the surface flux of that scalar and rendered dimensionless by scaling with <u'w'> produces a result that can be taken as a function of z/L alone. Hill further demonstrates that the dimensionless MOS functions for the variances and correlations of all possible SBL scalars are equal, a result which leads directly to the assertion implicit in Equation (4) that r_{TQ} is unity.

MOS theory has been successfully applied to SBL temperature and humidity variances and profiles (Wyngaard et al., 1978) and, because MOS scaling often works for these variables, it has been widely assumed that it will work for the temperature-humidity cross-structure parameter and therefore for C_n^2. Similarity arguments supporting this assumption are used by Andreas (1987a, 1988, 1989, and 1991) to define C_n^2 as a MOS quantity and to promote the use of dual-wavelength scintillation measurements for determination of path-averaged stability and heat flux. The assumption that MOS theory is applicable to C_n^2 has also found its way into atmospheric propagation models. Examples include McMillan et al. (1983) and McMillan and Bohlander (1987) for millimeter-wave (mmw) propagation, Paulus (1989) for evaporation duct modeling in stable marine environments, and Rachele and Tunick (1991) for unstable atmospheric conditions.

Although the treatment of C_n^2 as a similarity variable is very convenient, it is also at variance with reality. Hill (1989) demonstrates that application of the similarity concepts described above leads to the conclusion that all SBL scalars (including C_n^2) when "properly scaled" reduce to the same functional form, which requires that all of their normalized cospectra be either +1 or -1. Because this condition clearly does not exist in a real SBL, Hill (1989) concludes that this MOS prescription is an "overidealization" of SBL scalar behavior. Hill's conclusion is supported by Cook and Burk (1992), who demonstrate through a numerical analysis that potential refractivity χ cannot be treated as a similarity variable. They also conclude that refractivity, which is a less conservative scalar than χ, is even less suitable as a MOS quantity. Their numerical results await experimental verification.

2.2 EXPERIMENTAL EVIDENCE ON TEMPERATURE-HUMIDITY COHERENCE

Experimental verification of C_{TQ} and C_n^2 as MOS quantities hinges on acquisition of data to calculate r_{TQ}. Several decades of experimental evidence has been amassed on the subject of temperature-humidity interactions in the SBL over a variety of surfaces. The earliest measurements were obtained using fast-response hot-wire temperature probes and Lyman-α hygrometers, but other types of hygrometers have subsequently come into use. (A discussion of

instrumentation is presented in Section 2.4.) The results of experimental studies, most of which were performed over water surfaces, indicate that temperature-humidity interactions are complex and vary greatly with the state of the underlying surface, measurement height, and turbulence scale.

Friehe et al. (1975) investigated the effects of temperature and humidity fluctuations on the optical refractive index in the marine boundary layer. Their experiments were conducted over the open ocean with cold air blowing over warm water and over the Salton Sea with warm, dry air blowing over cold water. They found that, while humidity fluctuations make a negligible contribution to the mean optical refractive index, they can make a substantial contribution (primarily through the C_{TQ} term) to the statistical and spectral properties of refractive index fluctuations. When examined as a function of frequency, Friehe et al. (1975) found that the temperature-humidity cross-structure contribution to the refractive index power spectrum was substantial up to a frequency of 0.1 Hz. At higher frequencies, the temperature structure function alone became the dominant contribution to C_n^2. Friehe et al. (1975) also noted that the sign of r_{TQ} can be positive or negative, depending on the relative temperatures and moisture contents of the surface and atmosphere. For cold air blowing over warm water, they found the correlation between temperature and humidity to be positive, accounting for 17 percent of the refractive index variance. For warm, dry air blowing over cold water, r_{TQ} accounted for -268 percent of the refractive index variance, more than offsetting the positive contribution by the temperature variance. Friehe et al. (1975) conclude that the sign of the C_{TQ} term is determined by the product of the signs of the surface fluxes of heat and moisture and that correlations are weak when either of these fluxes are small.

The results of Friehe et al. (1975) are reinforced by those of Wesley (1976), Wesley and Hicks (1978), and Fairall et al. (1980). Wesley (1976) and Wesley and Hicks (1978) found that r_{TQ} over warm, moist surfaces is dependent on eddy size; r_{TQ} is near unity for the low frequency, flux-carrying eddies, but decreases at a rate proportional to the square root of frequency in the high frequency inertial subrange portion of the spectrum. Their data also support the contention that an ample supply of surface moisture and heat as well as substantial heat and moisture fluxes are required to maintain high temperature-humidity correlations. Fairall et al (1980) found r_{TQ} to vary between 0.4 and 0.8 over a range of frequencies and atmospheric stability conditions above an ocean surface.

Temperature-humidity coherence studies over land are less numerous, but more recent, than over water. Kohsiek (1982, 1988) found an r_{TQ} near 0.75 in an unstable SBL above a surface with partial snow cover at Table Mountain near Boulder, Colorado and a range between 0.8 and 0.9 at Cabauw in the Netherlands. The Andreas (1987b) measurements over a snow surface produced similar r_{TQ} results (0.8 ± 0.16). Priestley and Hill (1985) found temperature and humidity fluctuations to be generally well correlated or anticorrelated, but subject to intermittent correlation breakdowns due largely to the sporadic nature of temperature fluctuations during periods with unstable atmospheric conditions. Biltoft and Ewald (1988) observed temperature-humidity coherences to be generally low over a dry surface at Dugway Proving Ground, but the

sampling rate was not sufficiently high for this result to be considered definitive.

As indicated by the literature review summarized above, the available literature does not include adequate studies of temperature-humidity coherence over dry surfaces. This omission is important because changes in the availability of moisture over a drying surface can cause changes in the heat and humidity fluxes and r_{TQ}. When heated, a wet surface acts as a common source region for both heat and moisture fluxes, and temperature-humidity coherence should be high. The moisture flux typically diminishes as the surface drys, while the heat flux typically increases. At a severely dessicated site in the Gobi desert, Wang and Mitsuta (1991, 1992) observed downward water vapor fluxes during the daytime. They explain this phenomenon as the consequence of heat and moisture emanating from different source regions. Temperature-humidity coherence measurements were not available at the Gobi site, but it is difficult to conceive of an atmospheric process in which scalar quantities emanating from separate source regions become coherent. The behavior of temperature-humidity coherence over dry surfaces remains poorly understood principally because of the difficulty of obtaining reliable measurements when the moisture flux is small and heat stress on the instrumentation is large.

2.3 IMPORTANCE OF THE CROSS-STRUCTURE TERM

The argument against the common modeling assumption that r_{TQ} is unity would be somewhat heuristic except for the electrooptical propagation implications for the specific conditions usually associated with deserts. The contribution of the C_Q^2 term in Equation (2) to scintillation (i.e., C_n^2) at optical wavelengths is small, but the C_{TQ} term becomes significant when large moisture gradients are present. For example, the Salton Sea results of Friehe et al. (1975) provide an example in which the C_{TQ} term completely canceled the contribution of the C_T^2 term to C_n^2. The importance of the C_{TQ} term can be even more significant at infrared and millimeter wavelengths where the contribution of the C_Q^2 term to scintillation is usually dominant. If only a small amount of moisture is available, as is frequently the case over deserts, the C_Q^2 term can be reduced to near equality with the C_T^2 term, leaving the C_{TQ} term dominant. Under these conditions, the magnitude of r_{TQ} is of crucial importance.

Table 1 illustrates the sensitivity of mmw scintillation to the C_{TQ} term by calculating C_n^2 with r_{TQ} set equal to its two possible extreme values, 0 (5th column) and 1 (6th column). These computations were performed using Equation (2) with the mmw temperature and humidity sensitivity coefficients given by McMillan et al. (1983) and measurements made at DPG under hot, dry conditions (Biltoft and Ewald, 1988). When neither the temperature nor the humidity contribution to mmw C_n^2 is dominant, the data in Table 1 show that the uncertainty in the predicted C_n^2 can vary over several orders of magnitude, depending on the assumed value of r_{TQ}. It follows that large uncertainties can be present in the predictions of any target acquisition model that uses C_n^2 to parameterize mmw propagation if the correct magnitude of r_{TQ} is not known. The true value of r_{TQ} for the DPG data set remains unknown because of instrumentation limitations.

Table 1. Computations of mmw C_n^2 Using Equation (2) and August 1988 Dugway Proving Ground Measurements.[a]

Trial	$\frac{A_T^2 C_T^2}{\langle T \rangle^2}$	$\frac{A_Q^2 C_Q^2}{\langle Q \rangle^2}$	$\frac{2A_T A_Q C_{TQ}}{\langle T \rangle \langle Q \rangle}$	C_n^2 (r_{TQ}=0)	C_n^2 (r_{TQ}=1)
1A	50.29	29.52	-77.06	79.81	2.75
1B	40.47	16.33	-51.42	56.80	5.38
1D	50.21	19.47	-62.53	69.68	7.15
2B	1.50	16.82	10.03	18.32	28.35
3A	4.03	23.24	19.35	27.27	46.62
3B	5.42	23.63	22.62	29.05	51.67
4C	38.68	12.41	-43.82	51.09	7.27
4D	52.86	46.57	-99.23	99.43	0.20
5A	46.25	28.44	72.54	74.69	147.23
5B	6.97	17.27	21.94	24.24	46.18
6B	21.33	18.38	39.60	39.71	79.31
7A	28.38	27.87	-56.24	56.25	0.01

[a] Units for Equation (2) components are $m^{-2/3} \times 10^{-14}$.

2.4 MEASUREMENT REQUIREMENTS AND INSTRUMENTATION

Sampling speed and accuracy are the two major considerations for temperature-humidity coherence studies. Because fast-response temperature measurement technology is reasonably well developed, the major concern is with humidity instrumentation. Sampling rate requirements are determined by the scale of the desired measurements, which is defined by the wavelength and pathlength of the propagating wave. Water vapor sampling in arid conditions requires vapor density measurement accuracies on the order of ± 0.05 g m^{-3}, an accuracy that imposes stringent requirements for calibration stability and thermal stabilization. Flow distortion can also have a deleterious effect on measurement accuracy.

The turbulence scales that contribute to C_n^2 for a wave propagating over path length L are of a size comparable to the first Fresnel zone, $(\lambda L)^{0.5}$, where λ is the wavelength. For example, the pertinent scale of turbulence for optical propagation over a 1-km path is on the order of a centimeter. In the case of mmw propagation, the pertinent scale is on the order of several meters. Within the surface boundary layer, the turbulence scales relevant to optical propagation are near the lower end of the inertial subrange where viscous effects begin, while the scales that are significant for mmw propagation are likely to be closer to the energy-containing portion of the spectrum. Measurements made to define r_{TQ} for optical wavelength scintillation studies

must have extremely fast sampling rates (on the order of several hundred to one thousand Hertz), whereas those made for mmw studies can typically have sampling rates of several tens of Hertz. When a high sampling rate is the paramount consideration, probe contamination and calibration instability are the major experimental problems. At lower sampling rates, the principal concern becomes flow distortion by the instrument array. Fast-response temperature and humidity measurements usually are made using hot-wire thermometers combined with Lyman-α hygrometers. Thermocouples, sonic thermometers, and differential absorption hygrometers can be used for slower sampling rates.

Commercially-available instrumentation surveyed during the search for a fast-response humidity measurement capability consisted of three types: (1) the Lyman-α hygrometer (Tillman, 1965; Buck, 1977), (2) the krypton hygrometer (Campbell and Tanner, 1985), and (3) the differential absorption hygrometer (Nelson, 1982; Auble and Meyers, 1992). The advantages and limitations of these instruments are discussed below.

The Lyman-α hygrometer utilizes the 121.56-nm Lyman-α emission line of hydrogen, which is strongly absorbed by water vapor. Detection occurs in a nitric oxide ionization chamber that is separated from the receiver by a gap of 1 cm or less. Advantages of the Lyman-α design include high sensitivity, high frequency response (1 kHz or better), and excellent spatial resolution. Used in combination with fast-response hot wire thermometers, the Lyman-α hygrometer has been the principal source of high frequency temperature-humidity coherence data. Major limitations of the Lyman-α hygrometer are calibration instability, drift in gain due to clouding or etching of the source and detector windows, nonlinearity, and the short lifetime of hydrogen source tubes. An additional difficulty for all but the very small turbulence scales is the probe-induced flow distortion that causes deformation of the spatial structure of an advected scalar field (Wyngaard, 1988). A uranium hydride source can be used to extend tube life and diminish problems with calibration drift, but it also increases power consumption, cost, and complexity (Campbell and Tanner, 1985).

The krypton hygrometer is a variant on the Lyman-α design in which a krypton glow tube is used in place of the hydrogen tube, providing a longer tube life and improved calibration stability (Campbell and Tanner, 1985). Calibration is nearly linear for water vapor, but the 116.49- and 123.58-nm bands are also absorbed by atmospheric oxygen. The sensitivity of the krypton hygrometer to water vapor is less than that of the Lyman-α hygrometer, and its response to oxygen introduces nonlinearities that become a concern in dry conditions where the humidity signal is small. Additionally, the krypton hygrometer requires a temperature correction, and its small path length (several cm) is likely to generate flow distortion in the horizontal plane. However, the vertically symmetrical design minimizes flow distortion along the vertical axis. An example of the krypton hygrometer is the Campbell Scientific Model KH20. Its response time, which is in excess of 10 Hz, is sufficient for most moisture flux calculations.

Differential absorption hygrometers measure the water vapor along a path between a transmitter and receiver by determining the difference in transmitted energy for two frequencies, one in a strong water vapor absorption band (near 2.6 μm) and one outside this band (near 2 4 or 4.0 μm). A rotating chopper wheel assembly alternately passes narrow bandpass interference filters for the two frequencies in front of the transmitter. If the filters have good bandpass characteristics and identical sensitivities to temperature, solar radiation, and other potential interferents, the ratio of the signal $F_{2.6}$ received at 2.6 μm to the signal $F_{2.4}$ ($F_{4.0}$) received at 2.4 (4.0) μm is related to water vapor density ρ_v by (Connolly, 1991)

$$\frac{F_{2.6}}{F_{2.4}} = \left(\frac{1}{b}\right) \exp\left(\frac{-\rho_v \Lambda}{a}\right) \tag{6}$$

where a and b are determined experimentally and Λ is path length.

Of the three types of fast-response humidity sensors, the differential absorption hygrometer appears to be the most practical for routine field measurements because of the simplicity of its design and lack of obvious limitations. Also, differential absorption hygrometers designed with vertical symmetry and transmitter-receiver separation distances of 15 cm to 1 m more closely satisfy Wyngaard's (1988) flow distortion minimization criterion than the krypton or Lyman-α hygrometers. However, there is a tradeoff of decreased spatial resolution (because of the longer open path), slower response time, and increased mechanical complexity. Specific examples of the differential absorption hygrometer are the Infrared Absorption Gas Analyzer (Auble and Meyers, 1992), Ophir Atmospheric Infrared Hygrometer (Cerni et al., 1987), and Analytic Applications M100 Hygrometer (Connolly, 1991). Of these three models, the M100 hygrometer was chosen for the temperature-humidity coherence measurements in this study because it had the fastest reported data rate (80 Hz averaged to 10 Hz), a 15-cm path length compatible with the available sonic anemometer/thermometer's vertical velocity and (sonic) temperature measurements, vertical symmetry, and RS232 output.

2.5 TRIAL RESULTS

Several attempts were made during 1991 and 1992 to use Analytic Applications, Inc. M100 Hygrometers to determine temperature-humidity coherence over desert terrain. The first attempt was during the September 1991 Concentration Fluctuation Modeling of Chemical Hazards field test (Biltoft, 1991). Two M100 hygrometers were mounted adjacent to Applied Technologies, Inc. sonic anemometer/thermometers at 3 m above ground level. It was quickly determined that the chopper wheel motor speed would not stabilize, and the hygrometers were returned to the manufacturer for repair.

A second attempt to obtain temperature-humidity coherence data was made in March 1992. Two M100 hygrometers were mounted adjacent to a sonic anemometer/thermometer on a 3-m mast near the Tower Grid Command Post at Dugway

Proving Ground. A series of trial runs was made on a cloudy day with little direct solar radiation and on a clear day with strong solar radiation. Low frequency oscillations were observed in the hygrometer data on the cloudy day, indicating inadequate temperature control on the photodetector. The problem became worse on the clear day, indicating additional problems with background radiation and/or thermal stress on the photodetector housing. Analyses of spectra obtained from the March trials indicated that the data were unusable due to low frequency oscillations and unacceptable signal-to-noise ratios. Samples of the trial data and the hygrometers were sent back to the manufacturer for further modifications.

After minor modifications to the optics and electronics by the manufacturer, a third set of temperature-humidity coherence trials was performed in July 1992 at the same location and with the same setup as used during the March trials. New calibration curves supplied by the manufacturer and a sun shield were used to minimize low frequency oscillations in the data. Trials were conducted in intense heat (surface temperatures at or near 35 °C) over a dry surface and with low atmospheric moisture. The hygrometers were once again unable to produce satisfactory signal strength or maintain the photodetector temperature control needed to produce usable data. These trial results show that the M100 hygrometers suffer from basic design deficiencies. These deficiencies can be corrected only by a major redesign of the instrument.

Proposed M100 hygrometer modifications include a new direct-current (DC) brushless motor, a multi-stage cooler for improved temperature control, a larger aperture for increased sampling volume, baffles, and anti-reflective coatings for the optics. These modifications are in the process of testing and implementation, and should be completed by the spring of 1993.

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SECTION 3. APPENDICES

APPENDIX A

METHODOLOGY INVESTIGATION PROPOSAL AND DIRECTIVE

FY92

Test Center: DPG **MISSION AREA SUPPORTED: NBC**

Title: Desert Atmospheric Effects on Target Acquisition

PRINCIPAL INVESTIGATOR: Christopher A. Biltoft **Office:** STEDP-MT-M
Email Address: gross@dugway-emh2.army.mil **Autovon:** 789-5101

BACKGROUND: Target acquisition using optical, infrared, and millimeter-wave (mmw) techniques in desert terrain is impaired by scintillations due to intense heating near the ground surface. Temperature-humidity coherence has a particularly significant effect on mmw propagation.

PROBLEM: Deficiencies in instrumentation, particularly with fast-response hygrometers, have prevented satisfactory resolution of temperature-humidity coherence effects on propagation.

OBJECTIVE: Use recently developed fast response differential absorption hygrometers and sonic anemometer/thermometers, along with radiative flux measurements, to define coherence effects on propagation.

IMPACT/JUST: The mmw refractive index structure parameter will remain indeterminate until temperature-humidity coherence is measured. If it is not, model predictions of mmw propagation over desert terrain will remain uncertain.

PROCEDURES:

Target Date	Achievement
12/31/91	Complete literature search on mmw propagation and temperature-humidity coherence.
04/30/92	Begin series of measurements over representative desert terrain types.
08/30/92	Complete series of measurements over representative desert terrain.
09/15/92	Complete analysis and begin report preparation.

COST CATEGORIES:

± Personnel Compensation:	$20K
± Travel:	$0K
± Contractual Support:	$0K
± Consultants & Services:	$0K
± Materials & Supplies:	$0K
± Equipment:	$0K
± General & Admin costs:	$0K

± Man-hours Required:

± IN-HOUSE DIRECT LABOR:	600
± CONTRACT LABOR:	0

OBLIGATION PLAN:

obligation rate	FQ	1	2	3	4	TOTAL
(Thousands)		5.0	0.0	7.0	8.0	$20K

DEPARTMENT OF THE ARMY
HEADQUARTERS, U.S. ARMY TEST AND EVALUATION COMMAND
ABERDEEN PROVING GROUND, MARYLAND 21005-5055

REPLY TO
ATTENTION OF

AMSTE-TC-D (70-10p)

01 OCT 1991

MEMORANDUM FOR Commander, U.S. Army Dugway Proving Ground, ATTN: STEDP-MT-A, Dugway, UT 84022-5202

SUBJECT: Test Execution Directive, Test Technology Development Program

1. Reference TECOM Regulation 70-15, 16 Sep 91, Research, Development, and Acquisition - TECOM Test Technology Program.

2. This memorandum authorizes the execution of the projects listed in enclosure 1 under the TECOM Test Technology Development program. Detailed project descriptions listed in the FY92 TDAP database are the basis for headquarters approval of the projects.

3. Upon receipt of this directive, review TRMS II database test milestone schedules established for the projects and enter any necessary reschedules directly into the TRMS database with appropriate justifying narrative.

4. All safety, health, energy, and environmental issues associated with the project will be considered and necessary documentation or support studies/information/approvals required will be accomplished/prepared prior to project initiation. Security/OPSEC requirements will be adhered to.

5. All reporting, including final technical reports prepared by contractors, will be in accordance with the requirements and appropriate formats as specified in the references. Final reports will be reviewed and approved by Headquarters, TECOM, Directorate for Technology.

6. FY92 RDTE funds authorized for the projects are listed on enclosure 1. GOA Form 1006 will be forwarded by the TECOM Directorate for Resource Management, and will be updated to reflect all changes to current program. A cost estimate is to be submitted within 30 days following receipt of this directive.

AMSTE-TC-D
SUBJECT: Test Execution Directive, Test Technology Development Program

7. Point of contact at this headquarters is Cyndie McMullen, AMSTE-TC, amstetcd@apg-9.apg.army.mil, DSN 298-7881/7884.

FOR THE COMMANDER:

Encl

Kenneth Barlett
FREDERICK D. MABANTA
Chief, Technology Development Division
Directorate for Technology

CF:
Cdr, USADPG, ATTN: STEDP-MT-AT (Perry Pederson)

FY92 TEST TECHNOLOGY DEVELOPMENT PROGRAM

DUGWAY PROVING GROUND		CURRENT PROGRAM	SBIR "M" ACCOUNT CUT	CONG CUT	HOLD	1006 RELEASE
7-CO-M92-DPD-001	FY92 Quick Reaction Methodology	27.0	0.0	0.0	0.0	27.0
7-CO-M92-DPD-002	FY92 Technical Committee Support	10.0	0.0	0.0	0.0	10.0
7-CO-M92-DPD-003	Fluorometric Detection of Simulants	24.0	0.0	0.0	0.0	24.0
7-CO-M92-DPD-004	Anal of Special Chemical Warfare Agents	32.0	0.0	0.0	-10.0	22.0
7-CO-M92-DPD-005	Bio-Simulant Characterization	50.0	0.0	0.0	-50.0	0.0
7-CO-M92-DPD-006	Generation of Calibrated Gas Mixtures	36.0	0.0	0.0	-36.0	0.0
7-CO-M92-DPD-007	Aerosol Detection of Bio-Challenges	48.0	0.0	0.0	-48.0	0.0
7-CO-M92-DPD-008	Aerosol Penetration of Fabrics	25.0	0.0	0.0	-25.0	0.0
7-CO-M92-DPD-009	Desert Atmos. Effects on Tgt. Acquisition	20.0	0.0	0.0	-20.0	0.0
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	TOTAL DPG PROGRAM	272.0	0.0	0.0	-189.0	83.0

DUGWAY PROVING GROUND		CURRENT PROGRAM	SBIR "M" ACCOUNT CUT	CONG CUT	HOLD	1006 RELEASE
7-CO-R92-DPD-001	Develop Air Filtration System for Containment	175.0	0.0	0.0	0.0	175.0
7-CO-R92-DPD-002	Lidar Systems Improvement and Validation	180.0	0.0	0.0	0.0	180.0
7-CO-R92-DPD-003	Chamber Chemical Agent Monitoring Conceptual,	45.0	0.0	0.0	-45.0	0.0
7-CO-R92-DPD-004	Millimeter Wavelength Imaging Radiometer (MMW	150.0	0.0	0.0	-150.0	0.0
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	TOTAL DPG PROGRAM	550.0	0.0	0.0	-195.0	355.0

M92 = METHODOLOGY   R92 = RDI

APPENDIX B. REFERENCES

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